

1 Climate Information for Coping with Environmental Change: Contributions of the World Climate Research Programme

John A. Church, Ghassem R. Asrar, Antonio J. Busalacchi and Carolin E. Arndt

1.1 Introduction¹

Every day climate variability and change shapes the world, including the natural environment and its biodiversity on which society depends for water, food and other ecosystem services. Since the evolution of *homo sapiens* about 200,000 years ago, it is only in the last 10,000 years that we have moved from a hunter-gatherer existence to our modern society with its critical dependence on agriculture and exploitation of natural resources at an ever increasing rate. The relatively stable climate during the Holocene was an important component in making this transition possible (Burroughs 2005).

To provide the scientific basis for the provision of climate information that society has become increasingly dependent on, the *World Meteorological Organisation* (WMO), the *International Council for Science* (ICSU) and the *Intergovernmental Oceanographic Commission* (IOC) agreed to sponsor the *World Climate Research Programme* (WCRP). Since its inception, the two major objectives of the WCRP have been to determine a) the predictability of climate, and b) the effect of human activities on climate.

WCRP completes research projects designed to improve our knowledge of the climate system. It also develops observational programmes and models for knowing how climate has and is changing and how it

is likely to change in the future. This information is essential to help society respond to the threats and challenges and to overcome the vulnerability and risks associated with global climate and environmental change.

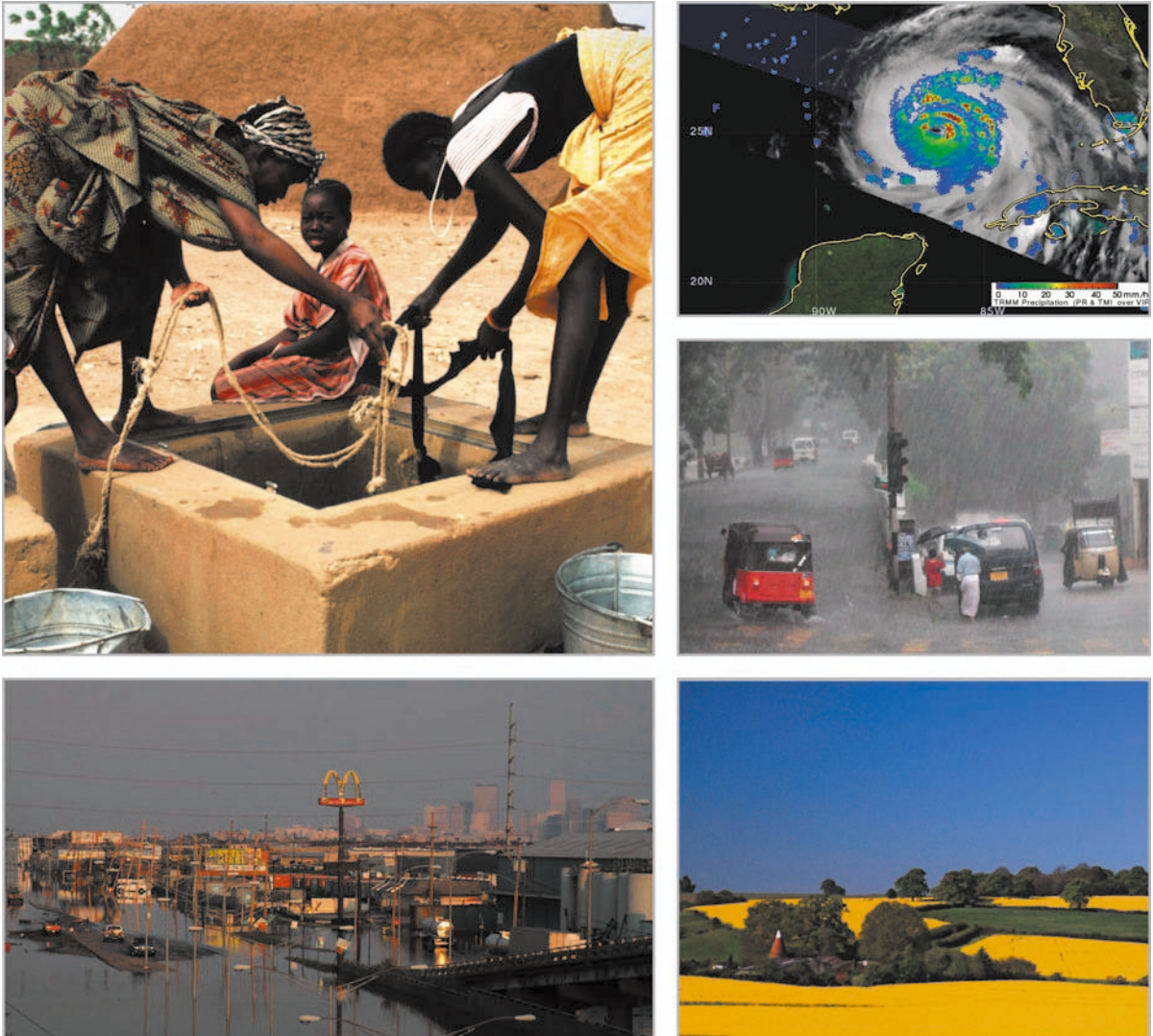
This chapter outlines the links between climate and society (1.2), requirement for useful climate information (1.3) and establishment of the WCRP (1.4). Then progress in addressing these issues over recent decades is reviewed (1.5) and challenges and opportunities for the future (1.6) and the strategy for the next decade are discussed, drawing on the *World Climate Research Programme Strategic Framework 2005-2015* (2005) and the *WCRP Accomplishment Report 2007-2008* (at: <<http://wcrp.wmo.in>>). Part 1.8 draws some general conclusions and highlights the policy relevance of the WCRP's achievements.

1.2 Climate and Society

Today, climate not only impacts on food and water supplies but it also has major impacts on human health, business, the economy and our society (figure 1.1). While our increasing mastery of technology and exploitation of energy reserves has given us some limited ability to adapt to climate variations and the associated environmental change, the burgeoning population of the world, increasing urbanization and the increasing demand we are making on our environment means that we are also becoming increasingly vulnerable to changes in climate, particularly as felt through extreme events such as floods, droughts, and other climate phenomena. These impacts are felt by the poorest of the poor struggling against drought or floods to the most well off in rich western nations devastated by the impact of events such as temperature extremes, hurricanes and storm surges. Failure to adequately plan for and respond to these climatic changes leaves society vulnerable to the impacts of

1 This chapter is a contribution to the CSIRO Climate Change Research Programme and Wealth from Oceans Flagship and was supported by the Australian Government's Cooperative Research Centres Programme through the Antarctic Climate and Ecosystems Cooperative Research Centre. JAC was partly funded by the Australian Climate Change Science Programme. The authors are grateful for the sustained support and sponsorship of WCRP for the past 30 years by the WMO, ICSU and UNESCO/IOC, and for the long-standing voluntary efforts of the scientific community.

Figure 1.1: Human well-being and local economies are severely affected by droughts and floods. Tropical storms and in particular, the torrential rains and high wind speeds associated with them, cause damage to lives and properties in the order of tens of billions US\$ worldwide. **Sources:** Photos clockwise from top left: J. Isaac: <FAO/13702/J.Isaac>; NASA: <www.travelblog.org/Rich>; SanSan Samuel: <www.freedigitalphotos.net/>, J. Barker Free Digital Photo; Texas Forest Service by Jan Amen.



disasters and conflict, and the associated security risks.

Examples of the sectors critically impacted by climate include:

- *Agriculture* is vital in all parts of the globe and in many developing nations' accounts for over 50 per cent of GDP. In 2007, the number of undernourished people was approaching 1 billion. Large changes in productivity occur in response to inter-annual climate variations. Famine is all too often the result of the deadly combination of drought
- and war. Exploiting the good years and preparing for the bad years are both important.
- *Potable water* is a critical resource and today about 1 billion people lack access to clean water. Water is also an important as an energy source, the extremes of which in the form of drought and floods also impact on agricultural productivity and the natural environment.
- *Health risk* from vector borne disease is directly related to climate variations and indirectly to climate through availability of food and water.
- *Temperature variations* affect the demand for energy for heating and cooling and also affect the

efficiency of power plants. Renewable energy from hydro, wind and solar power are all sensitive to climate variations and change.

- *Tourism*, an important industry for developed and developing nations, will only flourish with good weather and climate conditions.
- *The marine environment*, as a major source of protein, a haven for tourists and its role in transport is also directly impacted by climate variability and change.
- *Civil infrastructure*, in the form of dams, roads, bridges and ports, built to last several decades, is vulnerable to changes in climate on these same time scales.
- *Banking and reinsurance* are impacted by damage from severe weather/climate events such as prolonged droughts or severe floods, temperature extremes and through economic conditions related to climate.
- *The natural environment* is under many sources of stress, with climate variability and change adding significantly to these, leading to desertification and rapid losses in biodiversity.

Climate phenomena are many and varied. Hundreds of millions of people are affected by the monsoons of South and East Asia, Africa and the Americas. Sudden and severe onset of the monsoon can bring devastating floods and major loss of life. Failure of the monsoon brings drought and famine to millions. El Niño events and the associated droughts and floods affect nations surrounding the Pacific Ocean and more distant parts of the globe.

Perhaps the most important issue of our times is climate change resulting from the burning of fossil fuels. It will have far reaching and long lasting impacts on the natural environment and virtually every aspect of our existence on the Earth. Some aspects of climate change are clear - rising temperatures, changing rainfall patterns and rising sea level. But at what stage should climate change be considered 'dangerous'; for example will we cross a threshold leading to a disintegration of the Greenland and West Antarctic Ice Sheets and a sea-level rise of metres making many people stateless. These impacts are potentially severe affecting the whole globe, the lives of many millions and even the viability of some nations. Clearly these changes will directly affect human welfare, peace and security, as recognized by the award of the 2007 Nobel Peace Prize to the *Intergovernmental Panel on Climate Change* (IPCC) and Mr. Al Gore.

It is becoming increasingly clear that many of these climate variations are felt most acutely through

extreme weather events such as heat waves, cold snaps, sustained drought, hurricanes and typhoons. The frequency and intensity of these events are directly related to interannual and decadal variations in climate as well as longer-term changes in climate. Perhaps the clearest example is the intense hurricane activity in the Caribbean region and the southern United States of America in recent years. To understand what is happening to climate and why, and to effectively predict future conditions and their impact, we have to recognize the connection across the time scales from extreme events through seasonal and decadal climate variations to centennial climate change. Similarly, we have to consider the range of space scales; all impacts of climate are local but they occur in a global climate system, with individual events sometimes related to conditions on the far side of the world; climate is a global issue with regional and local consequences.

Today, knowledge of how weather varies and predictions of tomorrow's weather are important to our everyday life and a wide range of businesses. Accurate predictions are critical to avoiding disasters that can occur in response to extreme events. Similarly, knowledge of seasonal to interannual variations in climate, including improved predictions in many regions and sectors, are proving increasingly valuable for agriculture, fisheries, water supply management and in some regions for minimizing the impacts of diseases such as epidemic malaria.² Projections of climate change have already had and are continuing to have a huge impact on society. Agreeing to appropriate mitigation and adaptation strategies in response to human induced climate change is a huge challenge for society. Robust climate science is required to respond to this challenge. However, there remains uncertainty in both the short-term predictions of seasonal climate variations and the long-term projections of climate change, particularly at the regional and local scale where decisions about adaptation are made. Much of our current planning is for developments and infrastructure for the next few decades. On these time scales, both the signal of natural variability of climate and the change of climate in response to changes in greenhouse gas concentrations are important. Demon-

2 See: Palmer/Alessandri/Andersen/Canteloube/Davey/Délécluse/Dequé/Diez/Doblas-Reyes/Feddersen/Graham/Gualdi/Guérémy/Hagedorn/Hoshen/Keenlyside/Latif/Lazar/Maisonnave/Marletto/Morse/Orfila/Rogel/Terres/Thomson (2004).

strated skill in predicting the natural decadal variability in climate is urgently needed.

If the challenges facing society are adequately confronted and overcome, sustainable development is accomplished and the United Nation's *Millennium Development Goals* (MDGs) are achieved, society urgently needs robust climate science. This requires understanding of what is happening now to our climate, and what will happen over coming seasons, years and decades to centuries. Such information is critical to underpinning peace and security in the world.

There are three major challenges in the climate arena:

- *Improving our prediction of short term climate variability.* This includes improved observations and understanding of climate variability, extending the geographical range and the lead time of useful predictions. Specific issues to address include for example the timing and onset of monsoons, break periods in the monsoons, the next season's and year's rainfall and temperatures.
- *Reducing the uncertainty of projections of climate change, particularly at the regional and local scale.* Society needs robust prediction of how phenomenon such as the monsoons and *El Niño/Southern Oscillation* (ENSO) will change, how quickly sea level will rise, what long-term changes we are committing future generations to, what climate variations might be termed 'dangerous' and thus what are the appropriate long-term greenhouse gas stabilization levels.
- *Developing the capability to make decadal predictions of climate variations.* On decadal time scales, both natural climate variability and anthropogenic climate change are important. This is a new and developing area.³

All of these three challenges are closely related and felt most acutely through extreme events. It is essential to take a holistic view of the climate system if societies' demand for sound climate information is to be satisfied.

An additional and equally important challenge is building two-way communication between the climate science community and the many and varied stakeholders. This communication is required to ensure

that progress in the science is exploited for the benefit of society and the environment and to ensure the development of sound international and national climate policy. This policy and societal relevance also provides a greater focus for climate science itself.

1.3 Requirements for Useful Monitoring and Prediction of the Climate System

Climate varies on all time scales, from seasons to years, decades, and a century and longer. Adequately understanding and predicting it requires consideration of the sun, the atmosphere (including its chemical state and both the troposphere and the stratosphere), the hydrosphere, the oceans, the terrestrial regions, the cryosphere, the biosphere and the interactions between all of these spheres and with society.

Monitoring climate and thus knowing how the current state differs from previous climate condition, and why it differs, is in itself valuable for decision making by society. Beyond the time-scale of weather forecasts, the ability to predict climate depends on the behaviour of the parts of the climate system with a longer 'memory' of past conditions (including the oceans, the biosphere, and the cryosphere) and variation in the 'forcing' of climate by both natural and human-induced factors. These 'forcings' include variations in the solar radiation received from the sun, changes in aerosols in the stratosphere as a result of violent volcanic eruptions, changes in the properties of the land surface as a result of natural variations (for example changes in snow cover) and also human activities (for example deforestation). Perhaps most importantly in recent decades and for the coming century are increases in the concentration of greenhouse gases in the atmosphere that trap some of the outgoing long-wave radiation and thus heat the earth.

Significant advances have been made in quantitative predictions of the climate system over coming seasons. These predictions are dependent on the current state of the climate system and thus it is critical to have comprehensive observations if we are to accurately predict climate. Projections of climate on time scales of decades to centuries and longer are less dependent on the initial state of the climate system but they are critically dependent on the evolution of all components of the climate system, including those slowly evolving components. Observations and the understanding of the climate system are critical to the

3 Meehl/Goddard/Murphy/Stouffer/Boer/Danabasoglu/Dixon/Giorgetta/Greene/Hawkins/Hegerl/Karoly/Keenlyside/Kimoto/Kirtman/Navarra/Pulwarty/Smith/Stamner/Stockdale (2009).

development and testing of models needed to accurately simulate climate on all time scales.

To be valuable, climate predictions need to include uncertainty estimates that can be obtained by performing an ensemble of predictions with slightly different estimates of the climate system at the start of the prediction and/or slightly different model parameters and by rigorous comparisons with observations. The quantities predicted include the means, trends and statistical characteristics of a large number of quantities that may be of practical use, such as surface temperature, wind, precipitation, atmospheric chemical state, ocean state, soil moisture, snow cover, sea ice, and the state of the El Niño-Southern Oscillation and other climate phenomena. The time-scales for the predictions range from weeks to decades and to the projections of climate change over decades to centuries.

1.4 Recognizing the Need – Establishment of the World Climate Research Programme

The first World Climate Conference in 1979 focussed on the relationship between climate and humankind.⁴ The Conference recognized the importance of climate variability, the impact of extreme events and the potential for climate change to impact on all aspects of society. As a result, the Conference called for the establishment of the *World Climate Research Programme* (WCRP) as a principal component of the *World Climate Programme* (WCP). The WCRP was initially (since 1980) sponsored jointly by the *World Meteorological Organization* and the *International Council for Science*. The *Intergovernmental Oceanographic Commission* of UNESCO also established a climate programme in the 1980's. In 1993, these two activities were merged with WCRP, now jointly sponsored by WMO, ICSU and IOC.

A WMO/ICSU/IOC *Joint Scientific Committee* (JSC) is responsible for formulating the overall scientific concepts and goals of the WCRP and for organizing the required international co-ordination of research efforts. The activities of WCRP are organized

through a series of projects and working groups and increasingly through integration across the full spectrum of WCRP activities. WCRP is supported by its Joint Planning Staff and the individual projects are supported by International Project Offices.

Since its inception, the two major objectives of the WCRP have been to determine a) the predictability of climate, and b) the effect of human activities on climate. To achieve these objectives, the WCRP promotes and coordinates essential research into understanding the behaviour of the various components of the climate system and their interactions, and their relations to the broader Earth system and the needs of society. Particular foci of WCRP include:

- improving the knowledge and understanding of global and regional climate variability and change, and of the mechanisms responsible;
- assessing the evidence of significant trends in global and regional climates;
- developing and improving numerical models capable of simulating and assessing the predictability of the climate system over a wide range of space and time scales and suitable for operational predictions;
- investigating the sensitivity of the climate system to natural and human-induced change.

These objectives were reaffirmed at the *Conference on the WCRP: Achievements, Benefits and Challenges* in Geneva in August 1997 (WMO 1998), with the immediate research priorities:

- to assess the nature and predictability of seasonal to interdecadal variations of the climate system at global and regional scales, in order to provide the scientific basis for operational predictions of these variations for use in climate services in support of sustainable development;
- to detect climate change and attribute causes, and project the magnitude and rate of human-induced climate change, its regional variations and related sea-level rise, as needed for input to the WMO/UNEP *Intergovernmental Panel on Climate Change* (IPCC), the *United Nations Framework Convention on Climate Change* (UNFCCC), and other such Conventions.

WCRP now includes comprehensive investigations of all elements of the physical climate system (atmosphere, hydrosphere, oceans and cryosphere) and in partnership with the *International Geosphere-Biosphere Programme* (IGBP; chap. xy Noone/ Nobre/ Seitzinger) and other international programmes chem-

⁴ This conference was organized by the *World Meteorological Organization* (WMO), the *United Nations Educational, Scientific and Cultural Organisation* (UNESCO), the *Food and Agriculture Organisation* (FAO), the *International Council for Science* (ICS) and the *World Health Organisation* (WHO).

ical and biological components of the earth's climate system. WCRP's focus also includes the development of appropriate models for understanding the climate system, the rigorous testing of these models and their experimental use for prediction and projection on longer time scales of the climate system.

A critically important partnership is with the *Global Climate Observing System* (GCOS) and the *Global Earth Observations System of Systems* (GEOSS), to ensure the collection of sustained observations necessary for monitoring climate variability and change, understanding trends, and initializing models for the prediction of climate.

1.5 Addressing the Challenge: Achievements of the World Climate Research Programme

This section offers a brief overview of the achievements of WCRP since its formation.

1.5.1 Seasonal Climate Predictions

A number of centres around the world now produce regular predictions of climate conditions for the coming few seasons as a result of progress by the *WCRP Tropical Ocean-Global Atmosphere* (TOGA) Project (1985-1994) in understanding of tropical Pacific climate anomalies associated with the *El Niño-Southern Oscillation Phenomenon* (ENSO). This was a major breakthrough in climate forecasting and the TOGA project is widely recognized as being the first major success of the WCRP. The two most critical elements of the legacy of TOGA (Anderson/Sarachik/Webster 1998) are:

- An enhanced in situ and satellite observing system in the Pacific Ocean to monitor the evolution of El Niño events and to initialize models, and
- Coupled models capable of assimilating the observed data and providing useful predictions of conditions for the next few seasons in a number of regions of the world.

Through ongoing and increasingly integrated efforts of WCRP projects (CLIVAR, GEWEX, ACSYS/CliC, and SPARC), the skill of these models is increasing as the in situ observing systems are extended to other regions, improved satellite observing systems are implemented, greater understanding of associated processes such as the monsoons is achieved and the models are improved. The capability developed by the

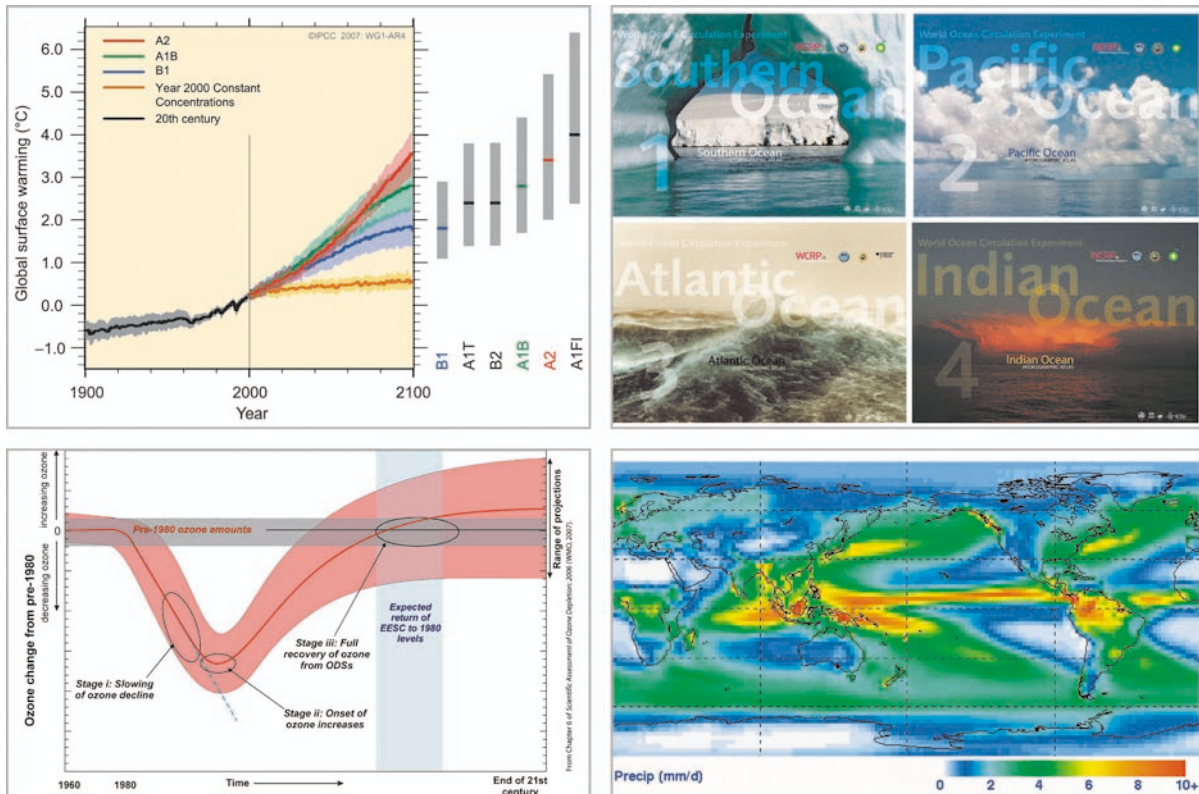
WCRP and now operational in a number of centres around the world are finding increasing application in a wide range of phenomena (for example minimizing the impact of epidemic malaria⁵, and a greater appreciation of their potential is recognized (WCRP 2008d).

1.5.2 Understanding, Observations and Models of the Ocean and Climate

The *World Ocean Circulation Experiment* (WOCE 1990–2002) completed the first set of global observations of the ocean (as documented in a four-volume WOCE Hydrographic Atlas, top right panel of figure 1.2) and thus the first quantitative assessment of the ocean circulation's role in climate. WOCE also developed ocean observing systems (both *in situ* and satellite-borne) and led to improved ocean models that are now proving critical to improved projection of climate variability and change. The WOCE survey established a baseline to assess changes in time and to evaluate anthropogenic effects on the global ocean circulation. In partnership with the *Joint Global Ocean Flux Study* (JGOFS), a CO₂ and tracer chemistry survey was completed allowing robust documentation of the oceanic uptake of CO₂. Developments in float technology during WOCE led to the Argo programme; the global deployment of an array of profiling floats to measure temperature and salinity profiles in the upper 2 km of the ocean. Experimental devices such as gliders have the potential for performing repeat sections in historically difficult to observe regions of the ocean, such as western boundary currents. These developments (particularly Argo) are now central observational components that underpin the development of climate prediction on decadal time scales and are critical in reducing uncertainties in the projection of climate change. The results are documented in almost 1800 refereed publications and summarized in Siedler, Church and Gould (2001). Much remains to be done in the exploitation of WOCE observations and in the further development of schemes to assimilate data into ocean models. These aspects of ocean research and model development are now being incorporated, as planned, into the WCRP *Climate*

5 See: Palmer/Alessandri/Andersen/Canteloube/Davey/Délécluse/Dequé/Diez/Doblas-Reyes/Feddersen/Graham/Gualdi/Guérémy/Hagedorn/Hoshen/Keenlyside/Latif/Lazar/Maisonnave/Marletto/Morse/Orfila/Rogel-Terres/Thomson (2004).

Figure 1.2: Illustrative examples of WCRP accomplishments. Clockwise from top left: Projection of global averaged temperature for the 21st century as prepared for the IPCC AR4 using the WCRP *Coupled Model Inter-comparison Project* results (IPCC 2007); The four ocean atlases produced by the WCRP *World Ocean Circulation Experiment*; Average global precipitation for 1979-2005 in mm per day (figure prepared by the WCRP-GEWEX Global Precipitation Climatology Project); Schematic observed and predicted evolution of global ozone (UNEP/WMO Scientific Assessment of Ozone Depletion: WMO 2006).



Variability and Predictability (CLIVAR) project, a successor to the TOGA and WOCE projects.

1.5.3 Snow, Ice, Frozen Ground and Climate

As demonstrated by the dramatic reduction in sea ice over the past few years, the Arctic region is both important for its role in climate and as a sensitive indicator of the impacts of climate change – how delicately balanced is the Arctic climate system? What is its role in global climate change? The achievements of the WCRP *Arctic Climate System Study* (ACSYS) Project provided: a basis for improved numerical simulations and reanalysis studies of the complex system involving polar atmosphere, oceans, sea-ice, and land; active development of an Arctic observing system, declassification of submarine sea-ice observations, generation of new satellite products, and collection and upgrading of circumpolar data sets; intercomparison projects which have led to advances in modelling of the polar

environment and created a better basis for projections of amplified impact of the climate change in the polar region (an important aspect of the IPCC assessments). These studies have now been extended world wide to include considerations of all aspects of the cryosphere (ice, snow, frozen land) through the ongoing WCRP *Climate and Cryosphere* (CliC) Project. An important example of which is the need for improved understanding of ice-sheet dynamics and the stability of the Greenland and Antarctic ice sheets in order to understand better the potential for extreme sea-level rise.

1.5.4 The Global Water Cycle

Water is a critical resource globally, especially in certain regions. Its representation in models is critical to reliable predictions of fresh water quantity, quality and distribution. Understanding its movement and recycling around the globe is a central focus of the on-

going WCRP *Global Energy and Water Cycle Experiment* (GEWEX) project. Accomplishments of GEWEX include global datasets of clouds, precipitation (bottom right panel of figure 1.2), water vapour, surface radiation, and aerosols which have provided new insights about seasonal, interannual and regional variability of fresh water. These data sets have underpinned implementation of improved representation of the land-surface and cloud in climate models and improved prediction of precipitation in many regional and global weather forecasting and climate models. On a regional scale, GEWEX scientists are making significant progress towards the full understanding of the regional water and energy budgets and are helping determine the importance of these processes for regional predictions of climate, thus enabling the comprehensive modelling and evaluation of the components of the water/energy cycle over large river basins.

1.5.5 The Stratosphere and Climate and Ozone

Trends in stratospheric temperature, vertical distribution of ozone, and upper tropospheric and stratospheric water vapour and their representation in models are an important focus of the ongoing WCRP *Stratospheric Processes and their Role in Climate* (SPARC) project and an important element of climate change.⁶ WCRP SPARC has made major contributions to the WMO/UNEP assessments of ozone depletion and IPCC climate assessments (lower left panel of figure 1.2), and is now working with the *International Geosphere-Biosphere Programme* (IGBP; chap xy by Noone/Nobre/Seitzinger) to significantly improve our knowledge of the representation of atmospheric chemistry and aerosols in the models that will be used for weather forecast and climate prediction. These efforts thus continue to support the Ozone and IPCC Climate Change Assessments.

1.5.6 Climate Change Detection, Attribution and Projection

The vast majority of the results assessed by the IPCC Working Group I in its successive reports are based on research and model projections organized and coordinated by the WCRP and the vast majority of authors are closely associated with WCRP. Indeed with-

out the model simulations coordinated by the WCRP there would be no climate change projections (top left panel of figure 1.2). Such WCRP coordinated results are the basis of key conclusions of successive IPCC scientific assessments such as the 4th Assessment Report (AR4) conclusions in 2007: “Warming of the climate system is unequivocal” and “Most of the observed increase in global average temperatures since the mid-20th century is *very* likely due to the observed increase in anthropogenic greenhouse gas concentrations.”

Improved understanding of key climate processes by WCRP has led to significantly improved climate and operational weather and ocean forecasting models. WCRP’s working groups have co-ordinated data analyses and climate model simulations that are the basis for our understanding of natural climate variability. In particular, improved modelling of the coupled physical climate system through systematic model diagnoses and intercomparisons has provided increasingly accurate simulations and predictions of natural climate variations, reducing uncertainty in their projections of human-induced climate change. In turn, the IPCC assessments provide the most authoritative, up-to-date scientific advice needed to inform the *United Nations Framework Convention on Climate Change* (UNFCCC). In this way, WCRP has helped provide the direct policy-neutral scientific underpinning of the political process. WCRP will continue to play an important role in helping to provide increasingly reliable climate change scenarios and making them (and their likely consequences) immediately available to decision makers, the media and the general public. These are critical contributions to deliberations on sustainable development, formulating mitigation and adaptation strategies, and managing the risks associated with climate variability and change on all sectors of the global environment and economy.

1.5.7 Global Climate Data Sets

Comprehensive climate observations are essential to climate prediction. Knowing how climate is changing underpins many societal needs. Provision of essential global and regional climate observations are major components of all WCRP projects. Some of these have evolved into new operational climate observations and data-collection systems. In particular: the buoy array in the tropical Pacific is crucial for monitoring and for initializing model predictions of ENSO events; systematic observations of the ocean’s three-dimensional structure, combined with satellite altime-

6 See: Ramaswamy/Chanin/Angell/Barnett/Gaffen/Gelman/Keckhut/Koshelkov/Labitzke/Lin/O’Neill/Nash/Randel/Rood/Shine/Shiotani/Swinbank (2001).

try have provided the basis for establishing key elements of a *Global Ocean Observing System* (GOOS) and, in turn, also the *Global Climate Observing System* (GCOS). Indeed, the worldwide network of operational ocean profiling floats (The Argo Project) is a direct outgrowth from the global array of subsurface floats that was established in WOCE. The TOGA and WOCE projects established a solid foundation for the operational oceanography of today, and tomorrow.

1.5.8 Historical Atmospheric and Oceanic Conditions

Modern atmospheric and oceanic models can be used to assemble comprehensive estimates of past conditions from the relatively sparse historical data sets. These estimates (called *reanalyses*) are important in understanding climate variations and change. WCRP has provided strong support for the initiation and execution of atmospheric reanalysis projects and such activities are now well established. Oceanic reanalyses have started in the last decade as a result of the WOCE and CLIVAR projects and will become increasingly important. These activities are a major outgrowth of the Third WCRP-sponsored *International Conference on Reanalysis* held in Tokyo, Japan, in January 2008 (WCRP 2008c).

1.5.9 Capacity Building

WCRP has enabled scientists from countries with less developed scientific programmes to contribute to the global programme and to build up their research capability. The global change *System for Analysis, Research and Training* (START) has been established by the *International Geosphere-Biosphere Programme* (IGBP), the *International Human Dimensions Programme on Global Environmental Change* (IHDP, chap. xy by von Falkenhayn/Rechkemmer/Young), and WCRP, to foster capacity building activities in developing countries, and thereby help them to become partners in international global change research. WCRP also benefits greatly from its partnership with regional networks such as the *Asia-Pacific Network* (APN) and the *Inter-American Research Institute* (IAI) to strengthen further its capacity building activities.

1.6 Challenges and Opportunities

The progress that WCRP has made in understanding the earth's climate system during the past 30 years and technological developments (in observations, computers and information systems, and telecommunication delivery mechanisms such as the internet) are enhancing our capability to serve increasingly greater segments of world society. This, coupled with the ever-increasing demand for reliable climate predictions and related products and services to establish policies to safeguard life and property and to better manage climate-sensitive natural resources and human developed systems and sectors, provides exciting new challenges and opportunities for WCRP. The challenges include:

- *Moving from daily/weekly weather forecasts to monthly, seasonal and longer-time climate prediction.* There is now a blurring of the distinction between shorter-term predictions and longer-term climate change projections and an increasing interest in demand for climate predictions for the next decade. These predictions will require knowledge of the current observed state of the climate system, particularly of the oceans, cryosphere, and land surface (including soil moisture, vegetation, etc.). Centennial climate projections also depend on scenarios for anthropogenic influence on the climate system and other factors, such as changes in the sun and volcanic eruptions which are not predictable but can be immediately taken into account as observed. The shorter time-scales and weather are important in influencing the longer-time-scale behaviour and the regional impacts of longer-term changes will be felt by society most acutely through changes in the shorter time-scale variability, including extreme events. As a result, and to obtain the information necessary for adaptation at the regional and local scale, climate models are being run with the highest possible spatial resolutions, resolutions that were employed in the best weather forecast models only a few years ago.
- *Environmental prediction and services.* The detailed physical prediction models of the coupled atmosphere, ocean and land system developed and used within WCRP are increasingly being extended to include atmospheric chemistry, the carbon cycle including evolving vegetation, and interactive marine ecosystems. It can be expected that full coupling with additional components of the Earth system will sometimes lead to quite different

behaviour, as has been found for coupled ocean-atmosphere models.

- *Predictability of the climate/Earth system.* An important underpinning of the progress in weather forecasting has been the development of chaos theory and the notions of predictability. An essential aspect of the move to making predictions of the broader climate/Earth system is to further develop these ideas to provide a firm foundation, giving ideas on what predictions to attempt and what techniques to use. The possibility that the increasing breadth of models may lead to compounding the uncertainties in them, and therefore increasing the uncertainty in model predictions, provides a challenge that will require new theoretical and observational approaches.
- *Analysis of climate system behaviour.* There is a continuing and urgent need to analyse the behaviour of the climate system, assess what has occurred, define anomalies and trends in the climate system, and determine the extent to which these can be attributed to human activity or to natural variation.
- *Application of WCRP science to socio-economic problems and demonstration of the usefulness of WCRP-enabled analysis and predictions.* There is increasing use of weather and climate information and prediction services and products on the time-scale of weeks to seasons, but much more work is needed to improve these products. For longer time-scales, the IPCC requires the best possible climate science and climate projections to provide the scientific basis for its periodic assessments and hence its advice to the Parties to the UNFCCC. Most impacts of climate change depend on its regional manifestation and there is great political and social demand for more confidence in assessments and predictions at regional and local scales.

The following developments mean that there is now a real opportunity to meet the above challenges and deliver vastly improved products to the wide range of stake-holders.

- *New and increasing data streams.* Enormous quantities of data are available from the environmental satellites (upper left panel of figure 1.3) already launched or planned. Also, the Argo system of ocean profiling floats (lower left panel of figure 1.3), developed under WCRP projects is becoming an increasingly important source of oceanographic data and an integral part of a developing ocean observing system for climate. These and

other *in situ* data are being integrated under the framework of the *Global Earth Observation System of Systems* (GEOSS), in order to optimize information products and services. They must be turned into quality-controlled climate data sets, requiring continuing pressure for observational data of climate quality and the continuous knowledge of data calibrations. Adhering to uniform international standards must be maintained as the observing system evolves.

- *The growth and availability of computing power.* The computing power becoming available (lower right panel of figure 1.3) means that in the future there will be an ability to run global models with resolution of a few kilometres (as required for many practical applications), very large model ensembles to assess uncertainty, simulations of paleoclimates with fully coupled global climate models, and, increasingly, highly-resolved regional models in response to the demand to develop adaptation policies and measures at the regional level.
- *An increase in the number of groups using global models.* As a result of greater and heightened attention to climate issues, there are now more groups capable of running climate models thus allowing the use of multi-model ensembles to overcome systematic deficiencies in single-model ensembles. This also increases the necessity to document the variety of model performance and understand the reasons for it.
- *The increasing complexity and realism of climate models.* High-resolution models including detailed physical parametrizations, cloud-resolving capabilities, and other detailed representations of relevant climate processes are being developed.
- *Modern data assimilation techniques applied to the Earth system models.* Numerical weather prediction has shown that maximum value can be obtained from the various streams of data by analysing them together in prediction models that are sufficiently accurate. This framework allows optimal state assessment based on past as well as present data. In the process, valuable information on model deficiencies can be obtained. Such data assimilation will increasingly be possible for the components of the coupled climate system and for the wider Earth system.

Figure 1.3: Satellite observations and in situ measurements taken in the ocean, the atmosphere and on land provide the basis for weather forecasts and climate predictions. The vast amount of observations collected on a daily basis is processed and then assimilated into models using the new generation of powerful computers. Training seminars in different parts of the world make sure that the users and decision makers properly understand and interpret the climate information products, and that the scientists receive feedback on the usefulness of their products and the users' needs. Images (top left to bottom right). **Sources:** ESA; Argo; www.ISRIC.org/V. van EngelenSOTER; JAMSTEC Earth Simulator Center.



1.7 Delivering on the Promise: The Future Strategy of the World Climate Research Programme

The WCRP has recognized the need to refocus its activities towards its original two aims and respond to the increasing demands of policy-makers and society for accurate and reliable climate predictions. As a result, WCRP developed its *Strategic Framework 2005-2015, Coordinated Observation and Prediction of the Earth System*. The aim of this WCRP Strategic Framework is: "To facilitate analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society" (at: <<http://wcrp.wmo.in>>).

This aim builds on the two overall objectives of WCRP that have guided its scientific activities for the

past 30 years to deliver the best available state of knowledge on climate variability and change to decision makers, in a manner consistent with the challenges/opportunities associated with the prediction of weather and climate across all time and space scales.

To meet this objective and to fulfil the existing and emerging societal needs for the best available knowledge of climate variability and change WCRP must focus its activities and partnership on five critical elements: 1) enhance understanding of the earth's climate system including the complex interactions among the major components (i.e. atmosphere, oceans, continents including the polar regions, and human activities), across the full spectrum of space and time scales; 2) support the continuity and innovation in observing systems to capture, document and analyse the state of the climate system; 3) exploit the resulting observations/information in conjunction

with climate models to predict and project earth's future climate; 4) enable the development of a climate information system to serve both the providers and users of observations and information in a timely and effective manner; and 5) establish a global network of experts (upper right panel of figure 1.3) to take full advantage of these capabilities to develop the best knowledge of the climate system for use by global, regional and local decision makers.

The focus is on developing mitigation and adaptation policies, strategies and solutions for managing the risks and opportunities associated with climate variability and change on major economic sectors (e.g. agriculture and food, water resources, energy and transportation, health and leisure, etc.). Some of these elements and/or their major components may exist today, but equally important is their integration and management as a continuum of activities to ensure efficient and timely delivery of the intended climate services to society in an effective and efficient manner. Such an approach will help shorten significantly the transition time from research and development to operations and services, thus meeting the emerging societal needs more efficiently. In short, developing a set of governance and operational principles is as important as the scientific and technical challenges associated with building and operating the climate information system.

The WCRP Strategic Framework facilitates addressing of these five elements by:

- integrating across the breadth of WCRP's projects and their activities;
- addressing the new challenges;
- regularly reviewing and assessing progress towards achieving the WCRP aims;
- identifying the emerging scientific objectives/priorities and addressing them in a timely manner;
- guiding existing and stimulating new scientific activities within WCRP;
- increasing recognition and visibility for the scientific and societal relevance and importance of WCRP results and their impact.

Partnerships are essential to the successful development and implementation of the climate information system. The broadening of WCRP interest in climate/Earth system studies is necessary for climate prediction and projection and implies the need for continued and strengthened collaboration with the *International Geosphere-Biosphere Programme* (IGBP), The *International Human Dimensions Programme* (IHDP), *DIVERSITAS* (a biodiversity programme)

and with the *Earth System Science Partnership* (ESSP) as a whole. The seamless nature of the prediction problem and of many of its applications implies that close collaboration and coordination are also needed with the WMO *World Weather Research Programme* and its projects such as THORPEX. Ensuring that WCRP-developed scientific knowledge is used in an appropriate and timely fashion for an increasing number of practical applications also requires close collaboration with the other principal components of the WMO World Climate and Water Programmes, and their network of providers and users of climate information, e.g. *Regional Climate Outlook Forum* (RCOFs) and *Regional Climate Centres* (RCCs).

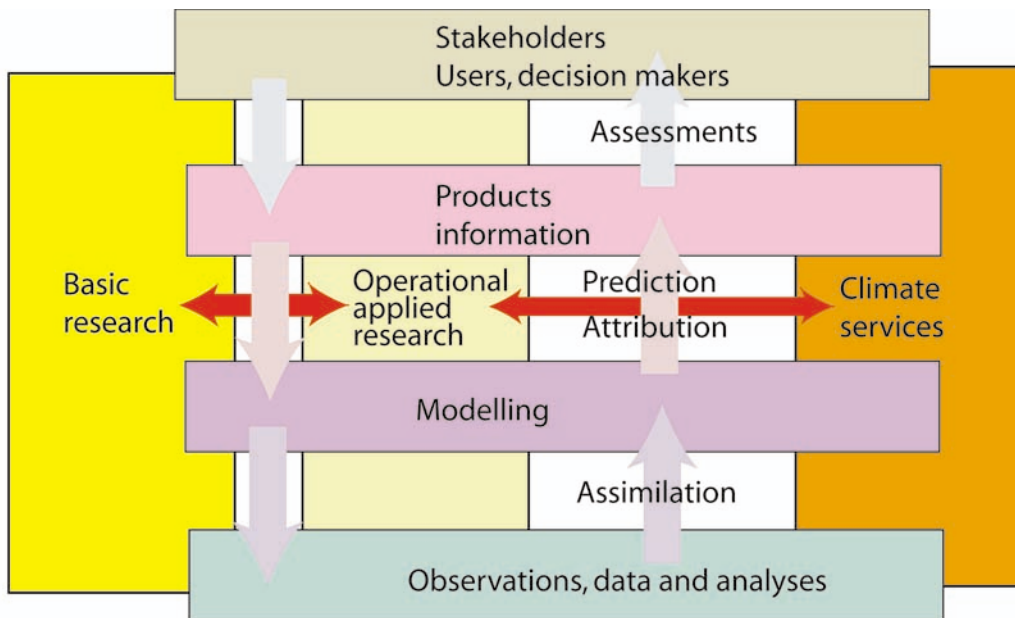
WCRP has taken a number of steps towards building the climate information system and network of experts with the aim to provide the best knowledge and information on climate variability and change to existing and emerging users of such information for decision making. These include:

- Before the *Fourth Assessment Report* (IPCC AR4) was completed, the WCRP in conjunction with IGBP had begun design of the set of model simulations that will underpin the climate change projections of the next IPCC report (Hibbard/Meehl/ Cox/Friedlingstein 2007).
- Initiated a new field of climate science to provide the first ever coordinated set of decadal climate predictions.⁷
- With the *Global Climate Observing System* (GCOS) and the *International Geosphere-Biosphere Programme* (IGBP), the WCRP identified the key areas of scientific uncertainties in the AR4 (IPCC 2007) that need to be addressed by the climate observation and research communities during preparations for the Fifth IPCC Assessment Report.⁸
- With the *World Weather Research Programme* (WWRP) and the IGBP, the WCRP convened the *World Modelling Summit for Climate Prediction*. This summit made a clear statement calling for a revolution in climate prediction, requiring vastly

7 Meehl/Goddard/Murphy/Stouffer/Boer/Danabasoglu/Dixon/Giorgetta/Greene/Hawkins/Hegerl/Karoly/Keenlyside/Kimoto/Kirtman/Navarra/Pulwarty/Smith/Stamner/Stockdale (2009)

8 See: WCRP (2008a); Doherty/Bojinski/Henderson-Sellers/Noone/Goodrich/Bindoff/Church/Hibbard/Karl/Kajfez-Bogataj/Lynch/Parker/Prentice/Ramaswamy/Saunders/Simmons/Stafford/Smith/Steffen/Stocker/Thorne/Trenberth/Verstraete/Zwiers (2009).

Figure 1.4: A schematic of the flow of the climate information system, as basic research feeds into, and responds to the needs of, applied and operational research and the development of climate services. The system is built on the climate observing system that includes the analysis and assimilation of data using models to produce analyses and fields for initializing models; the use of models for attribution and prediction, and with all the information assessed and assembled into products and information that is disseminated to users. The users in turn provide feedback on their needs and how to improve information. **Source:** This figure was developed by K. Trenberth (2008: 18) and slightly modified by G. Asrar.



- increased computing resources and appropriate personnel to develop further climate system models and verify their accuracy and adequacy, (Shukla/Hagedorn/Hoskins/Kinter/Marotzke/Miller/Palmer/Slingo 2009; Heffernan 2008). The resources required for such a Climate Prediction Project are small compared with the very large sums that will be required to develop solutions based on adapting to and mitigating the impacts of climate variability and change on aspects of our daily life, globally.
- Developed a series of cross cutting initiatives within WCRP to address critical and complex issues with tremendous societal impacts, including improved seasonal predictions (WCRP 2008b), the initiation of decadal predictions as referred to above, narrowing uncertainty regarding sea-level rise⁹; greater coordination of monsoon research activities in Asia, America, Africa and elsewhere; consideration of how to more effectively address the frequency and intensity of extreme events.

- Provided scientific expertise and coordinated research projects of the *International Polar Year*, leading to the agreement to establish a *Global Cryospheric Watch*.
- Established (for the first time and based on the need identified by the UNFCCC, IPCC and WCRP constituencies) a *Regional Climate Modelling and Downscaling Task Group* to help with identifying scientific and technical foci for WCRP activities during the next decades.
- With the *International Geosphere-Biosphere Programme* undertaking a joint activity to significantly improve the atmospheric chemistry and the representation of aerosols and cycling of carbon in the climate system models that will be used in future IPCC assessments.

The *Third World Climate Conference* (WCC-3) occurred in September 2009, 30 years after the first one. It is now the right time to propose and promote establishing a *Global Climate Information System* (figure 1.4). Such a system undoubtedly depends on the major components of observing systems that have been developed through international coordination and cooperation (e.g. *Global Climate Observing System*, etc.) and those under development. It must also

⁹ See WCRP (2006); Church/White/Aarup/Wilson/Woodworth/Domingues/Hunter/Lambeck (2008); Church/Woodworth/Aarup/Wilson (2009).

Figure 1.5: Climate adaptation solutions (clockwise from top left): A water reservoir in Africa; a barrier for protection from ocean storms protection; flood bunker in Bangladesh for protection during storm surges; water management and irrigation in China; flood prevention at the Thames barrier. **Sources:** <Treehuggerwww.PlayPumps.org>; International Federation of Red Cross and Red Crescent Societies (IFRC); UK Environment Agency; <www.WIKIMEDIA.org by J. Gao>.



take full advantage of the information management systems developed during the past 20 years, and the network of national and international global change research programmes, such as WCRP. However, to meet the challenges and opportunities identified earlier, operation and governance associated with this system must consider all components of the information system to be of equal importance and manage the two-way flow of information and decisions as a continuum. This implies that a weak link in this continuum will impact on the effectiveness of the system as a whole in capturing the required observations upstream and the timely delivery of required information to decision makers downstream. Another critical component of the system is an effective two-way communication between the climate science community and the rapidly growing user community and other stakeholders who are dependent on climate information. A number of examples of such operational Cli-

mate Information Systems are now being considered and implemented in several nations.

One very good example for the use of this system is the existing *UN Framework for Climate Change* (UNFCCC) that has been in place for more than 20 years and is attempting to enable nations from around the world to develop environmental policies based on the best available scientific assessments. While there are many options for adaptation to the impacts of climate variability and change (figure 1.5), if these options are to be effective they all need to be supported by sound climate information (understanding, monitoring and robust predictions) and effective communication of that information to users and stakeholders.

1.8 Conclusions and the Science Policy Interface

WCRP has played a key role in encouraging and coordinating the very best of climate science that society needs to meet the challenges of *global environmental change* (GEC) and bringing this information to the attention of policy-makers and the public.

It was the international community of physical climate scientists that alerted the world to the reality of global warming, the prospect of anthropogenic climate change and its consequences. It is this same community that has determined the most likely causes of the recent global climate change and which has the capability to provide increasingly reliable climate change scenarios, which are crucial for many aspects related to planning for sustainable development.

Through the IPCC Assessments, WCRP has helped bring such climate-related issues to centre-stage by carrying out policy-relevant science and raising the level of scientific, governmental and public appreciation of the importance of climate issues, through fostering much greater cooperation between hitherto distinct scientific disciplines in understanding the whole climate system. As reviewed above, the vast majority of the results assessed by the IPCC Working Group I in its successive reports are based on research and model projections organized and coordinated by the WCRP and the vast majority of authors are closely associated with WCRP. Indeed without the model simulations coordinated by the WCRP there would be no climate change projections. Such WCRP coordinated results are the basis of key conclusions of successive IPCC scientific assessments such as the 4th *Assessment Report* (AR4) conclusions (IPCC 2007). In turn, the IPCC assessments provide the most authoritative, up-to-date scientific advice needed to inform the UNFCCC. In this way, the WCRP has helped provide the direct policy-neutral scientific underpinning of the political process. In recent years, the WCRP, together with the *Earth System Science Partnership* (ESSP; chap. xy by Leemans/Rice/Henderson-Sellers/Noone), has developed a dialogue directly with the Parties to the *United Nations Framework Convention on Climate Change* (UNFCCC). Similarly the work of the WCRP is directly relevant to the WMO/UNEP Ozone assessments, the *UN Convention on Biological Diversity* (CBD) and the *Millennium Ecosystem Assessment* (MA), and the *UN Convention to Combat Desertification* (UNCCD) and of course directly underpins the achieve-

ment of a number of the UN's Millennium Development Goals (MDGs).

The WCRP will continue to play an important role in helping to provide increasingly reliable climate information and making them (and their likely consequences) available to decision-makers, the media and the general public. These are critical contributions to deliberations on sustainable development, formulating mitigation and adaptation strategies, and managing the risks associated with climate variability and change on all sectors of the global economy.

A critical further step is the development of a global climate information system that can capture the best available observations, climate system projections, and the expertise of best minds from around the world to translate the available knowledge in a form and format that is useful to decision-makers, and provide easy and timely access to such information is the best gift that we can offer our generation, our children and those who will follow them. Such a system would be significant contribution to the UN's *Millennium Development Goals* (MDGs) and responding to the threats, challenges, vulnerabilities and risks of global environmental change. This is indeed what the world expects from WCRP and its scientists and partners.

